PATENT APPLICATION

PUMPS FOR FILTRATION SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application Serial No. 60/446,830, entitled "In-Line Reverse Osmosis Pump", filed on February 11, 2003, and is a continuation-in-part of PCT Application Serial No. PCT/US02/22618, entitled "Dual Head Driven Membrane System", filed on July 16, 2002, which claims priority to U.S. Provisional Patent Application Serial No. 60/305,912, entitled "In-Line Reverse Osmosis Pump", filed on July 16, 2001.

This application is also a continuation-in-part of U.S. Patent Application Serial No. 09/907,092, entitled "Portable Water Disinfection System", filed on July 16, 2001, which is a continuation-in-part of, and claims priority to, U.S. Patent Application Serial No. 09/318,468, entitled "Portable Water Disinfection System", filed on May 25, 1999, now issued as U.S. Patent No. 6,261,464; and which is a continuation-in-part of U.S. Patent Application Serial No. 09/514,431, entitled "Portable Disinfection and Filtration System", filed on February 28, 2000, which is a continuation-in-part of U.S. Patent Application Serial No. 09/318,469, entitled "Portable Water Filtration and Pump System", filed on May 25, 1999; and which is a continuation-in-part of U.S. Patent Application Serial No. 09/579,178, entitled "Portable Water Disinfection System", filed May 24, 2000, now issued as U.S. Patent No. 6,524,475; and which is a continuation-in-part of U.S. PCT/US00/14513, entitled "Portable Disinfection and Filtration System," filed May 25, 2000; and which is a continuation-in-part of U.S. Patent Application Serial No. 09/686,214, entitled "Portable Hydration System," filed October 10, 2000; and which claims priority to U.S. Provisional Patent Application Serial No. 60/266,659, entitled "Mixed Oxidant Electrolytic Cell," filed February 5, 2001.

This application is also a continuation-in-part of U.S. Patent Application Serial No. 10/382,971, entitled "Filtration Membrane and Method for Making Same", filed on March 5, 2003,

which is a continuation of PCT application Serial No. PCT/US00/33254, entitled “Reverse Osmosis Membrane and Process for Making Same,” filed December 8, 2000, which claims priority to U.S. Provisional Patent Application Serial No. 60/230,895, entitled "Reverse Osmosis Membrane and Process for Making Same," filed on September 5, 2000. The specifications and claims of all of the references listed are incorporated herein by reference.

GOVERNMENT RIGHTS

The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of Contract No. DABT63-98-C-0052 awarded by U.S. Defense Advanced Research Projects Agency.

BACKGROUND OF THE INVENTION

Field of the Invention (Technical Field):

The present invention relates to removing particulate and dissolved solids from water by spiral wrapped membrane elements utilizing a dual diaphragm pump system that preferably incorporates pressure recovery, pulsing, fixed recovery (ratio of permeate to feed), and thin feed spacer spiral wrapped membrane elements. The maximum benefit of the system is achieved when reverse osmosis ("RO") is utilized as the membrane technology due to the high pressures inherent in RO membrane processes. However, the system of the present invention is also effective on microfiltration, ultrafiltration, nanofiltration, and other membrane systems. More particularly the present invention relates to alternative means to increase the production of potable water per unit size of membrane element and to reduce the energy cost per unit volume of water treated.

The present invention further relates to a reverse osmosis hand held pump with pressure recovery and in-line components for easy fabrication.

Background Art:

Removing impurities from drinking water supplies is a major factor in reducing the health risks to the human population. High levels of total dissolved solids (TDS) in water, such as dissolved salts in seawater, make the water unfit for drinking because of the ion imbalance in the human system. Most drinking water in the world today comes from ground or surface water sources and potable water from these sources is produced at small and large municipal drinking water treatment plants. A very small percentage of drinking water is produced from de-salination facilities. There are many settings in which these large systems are not practical. For example, campers, military personnel, and disaster relief situations require small man-portable systems that can treat water from just about any water source to produce potable water. To be effective in such remote settings, a system must be capable of repeated operation with little operator skill, no external power sources, and very little maintenance.

To be fully comprehensive, water filtration must include the capability for both conventional filtration as well as desalination. Conventional filtration can remove particulates that cause turbidity such as dirt, silt, sand, and larger organisms such as Giardia and Cryptosporidium. Reverse osmosis ("RO") technology must also be included to remove ions from such sources as sea water. At sea water concentrations of 35,000 milligrams per liter (mg/L), the system must be effective enough to remove ions to levels less than 1000 mg/L. While sodium and chloride are the two ions of concern in sea water, the system must be able to remove other ions as well. All of these ions are collectively known as TDS.

Existing technology removes TDS utilizing RO technology. Manual pumps utilize a pressure recovery feature to reduce the applied force required to generate the pressure needed to drive the RO process. U.S. Patent No. 3,749,524, to Jordan, entitled "Manually Operated Pump Utilizing Backpressure for Easement of Pump Stroke," discloses a pressure recovery feature for a pneumatic application. This feature does not apply to fluids such as water and lacks an efficient valve system for retentate discharge and for isolating the RO element in the event that

TDS removal is not required. U.S. Patent No. 4,124,488 to Wilson, entitled "Water Purification by Reverse Osmosis," and U.S. Patent No. RE 33,135, to Wanner, Sr. et al, entitled "Pump Apparatus," disclose a reverse osmosis pump mechanism with a pressure recovery feature. The present invention addresses the current problems by incorporating a simple valve mechanism for retentate discharge.

U.S. Patent No. RE 32,144, to Keefer, entitled "Reverse Osmosis Method and Apparatus," discloses a pump mechanism with pressure recovery and accumulator for reverse osmosis. The mechanism does not incorporate an efficient pressure relief and retentate discharge mechanism integral to the piston and rod assembly.

U.S. Patent No. 5,496,466, to Gray, discloses a portable water purification system with a double piston pump comprising a feed water piston in a feed water cylinder, a concentrate pumping section for removing concentrate from concentrate output, and a concentrate pumping section including a concentrate cylinder and piston wherein the pistons move in opposite axially directions. Gray does not teach differential pressure control or use of a spring or other mechanism for storing energy to average out the forces of the respective strokes. Further, Gray teaches use of a two-piston system only.

U.S. Patent No. 5,503,736, to Schoenmeyr, discloses a booster pump for a reverse osmosis water purification system wherein the pump has a spring return piston stroked by the pressure of feedwater and a pair of solenoid control valves (controlled by a piston position detector switch) that control the flow of feedwater into and out of the pump to move the piston between stroke and return positions. The Schoenmeyr patent, while disclosing a single piston, employs a two-headed piston with solenoid control valves and a control circuit system, unlike the differential pressure activated valve of the present invention.

Additional tangentially related prior art includes: U.S. Patent No. 5,589,066, to Gray; U.S. Patent No. 5,865,980 to Patapoff et al.; U.S. Patent No. 3,966,364, to Bachle et al.; U.S. Patent No. 5,531,887, to Miers; U.S. Patent No. 4,740,301, to Lopez; and U.S. Patent No. 3,830,372, to Manjikian.

SUMMARY OF THE INVENTION (DISCLOSURE OF THE INVENTION)

The present invention is of a pumping apparatus and method comprising: a dual head pump comprising a primary feed head comprising a feed diaphragm and a secondary retentate head comprising a retentate diaphragm; pumping fluid to at least one membrane surface; transferring force from the retentate diaphragm to the feed diaphragm to recover energy; providing a fixed recovery via the two heads; and imparting a pulsing pressure wave on the membrane surface. In the preferred embodiment, pumping fluid comprises providing feed fluid to a reverse osmosis membrane, preferably with at least one thin feed spacer element, and most preferably with at least one spiral wrapped element. Differential pressure is provided by a dual activated valve, pulsing is preferably hydraulic, and a plurality of membrane surfaces are provided, preferably wherein the spacing is reduced between the membrane surfaces to improve diffusion.

The present invention is also of a filtration system which provides an optimized pulsed fluid flow to a filtration element. The system comprises a pump, preferably a diaphragm pump, which preferably comprises a primary feed head and a secondary retentate head comprising different swept volumes. The heads are preferably connected either mechanically or hydraulically, wherein a force on the retentate head offsets the pumping force on the feed head. The filtration system preferably comprises a differential pressure activated valve, which seals the discharge port of the retentate head when the feed pressure exceeds the retentate pressure. The connection between the heads and the valve provide a pressure recovery to the system, reducing the energy required to operate the system. The filtration element is preferably a reverse osmosis element, preferably comprising a spiral wrapped element which comprises at least one

membrane and at least one thin feed spacer, which preferably comprises a plastic web mesh. The spacer is preferably less than about .025 inches thick, and more preferably less than about .011 inches thick.

The filtration system preferably comprises automatic and/or manual controls to vary parameters of the system to optimize the permeate quality, flow rate, and system energy requirements. The parameters are preferably pulse frequency and pulse amplitude. The system optionally comprises at least one quality measurement device, including but not limited to a flow meter, conductivity meter, and/or ammeter, and optionally comprises a feedback loop to vary the parameters.

The present invention is also of a method for filtering a substance comprising the steps of providing at least one filtration element; providing a pump which pumps a pulsed flow of the substance to the filtration element; and varying at least one parameter of the pulsed flow to optimize a desired characteristic of permeate filtered by the filtration element and the pump. The pump is preferably a dual head diaphragm pump in which the heads are connected in order to provide pressure recovery, thereby reducing the energy required to filter the substance. The method preferably comprises the step of sealing a discharge port of a retentate head when a feed pressure exceeds a retentate pressure, preferably using a differential pressure activated valve. The filtration element is preferably a reverse osmosis element, preferably comprising a spiral wrapped element which comprises at least one membrane and at least one thin feed spacer, which preferably comprises a plastic web mesh.

The step of varying at least one parameter of the pulsed flow preferably comprises varying the pulse frequency and the pulse amplitude, and preferably further comprises measuring a desired characteristic of permeate, including but not limited to the permeate flow rate, the total dissolved solids in the permeate, and the amperage load on the pump. The method optionally

comprises providing a feedback loop to automatically vary the parameter of the pulsed flow, thereby optimizing the desired characteristic of the permeate and pump.

The present invention is additionally of a pressure recovery filtration system comprising a dual head pump comprising a primary feed head, a secondary retentate head and a connection between the two heads; a filtration element; and a hydraulically actuated differential pressure activated valve. The heads preferably comprise diaphragms. The connection is preferably mechanical, optionally comprising a shaft, or alternatively hydraulic. The force on the secondary retentate head preferably offsets the force on the primary feed head. The valve preferably seals the discharge port of said retentate head when a feed pressure exceeds a retentate pressure, and preferably comprises an inlet port connected to said retentate head and an inlet port connected to said feed head. The valve preferably actuates according to a relative pressure difference between said inlet ports.

The present invention is further of a membrane filtration system comprising a piston which separates a feed chamber from a retentate chamber; a membrane filtration element; and a differential pressure activated (DPA) valve which controls the retentate discharge; wherein pressure recovery is provided by a pressure difference between the feed chamber and the retentate chamber acting on the piston. The pressure recovery is preferably significant enough to enable manual pumping of the piston, preferably at a recovery level of about fifty percent. The DPA valve is preferably hydraulically operated, with its operation determined by the relative pressure in the feed chamber and the retentate chamber, so that it operates automatically in accordance with pumping of the piston. The piston preferably comprises a piston shaft, the cross-sectional area of which determines the recovery ratio of the membrane filtration element. The piston shaft is preferably easily replaced, thereby enabling rapid change of the recovery ratio. The system preferably comprises a pressure relief valve.

The membrane filtration system preferably comprises a single cylinder and has a diameter of less than approximately four inches, and more preferably less than approximately two inches. The system preferably has a length of less than approximately twenty-four inches, and more preferably less than approximately fifteen inches. The system preferably weighs less than five pounds, and more preferably less than three pounds. The membrane filtration element preferably comprises a reverse osmosis element, which preferably comprises a spiral wrapped element preferably comprising at least one membrane and at least one thin feed spacer. The spacer optionally comprises a plastic web mesh and is preferably less than approximately .025 inches thick, and more preferably less than approximately .011 inches thick. The thin feed spacer provides for a reduction in an amount of total dissolved solids at a surface of said membrane.

The invention is also of a method of filtering a substance comprising the steps of pumping the substance with a piston, wherein the piston separates a feed chamber and a retentate chamber passing the substance through at least one membrane filtration element, preferably a reverse osmosis filtration element, thereby separating the substance into permeate and retentate; and discharging the retentate using a differential pressure activated (DPA) valve.
The method preferably comprises operating the DPA valve hydraulically, preferably according to the relative pressure in the feed chamber and the retentate chamber. This operation is preferably automatic as the substance is pumped. The method further comprises utilizing a pressure difference between the feed chamber and the retentate chamber acting on the piston to reduce the force necessary to pump the substance, preferably to a level that enables manual operation of the system.

A primary object of the present invention is to provide an improved filtration system for TDS reduction that provides potable water.

Another object of the present invention is to provide an improved filtration system that is compact in size for one person to easily carry. A further object of the present invention is to

provide an improved filtration system that can be operated purely with manual power as the only energy source.

A primary advantage of the present invention is a pressure recovery feature in the pump that utilizes a simplified valve mechanism for retentate discharge.

Another advantage of the apparatus is a pulsing mechanism in the pump that minimizes polarization concentration in the RO membrane thereby significantly reducing the applied pressure and improving the permeate flux produced for a given amount of power applied to the pump.

Other objects, advantages and novel features, and further scope of applicability of the present invention will be set forth in part in the detailed description to follow, taken in conjunction with the accompanying drawings, and in part will become apparent to those skilled in the art upon examination of the following, or may be learned by practice of the invention. The objects and advantages of the invention may be realized and attained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated into and form a part of the specification, illustrate one or more embodiments of the present invention and, together with the description, serve to explain the principles of the invention. The drawings are only for the purpose of illustrating one or more preferred embodiments of the invention and are not to be construed as limiting the invention. In the drawings:

Fig. 1 is a block diagram of the dual head pump filtration system of the present invention.
Fig. 2 is a block diagram of the in-line pump filtration system of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

(BEST MODES FOR CARRYING OUT THE INVENTION)

Dual-Head Pump

The present invention is of a motor driven dual headed pump that incorporates a differential pressure activated ("DPA") valve to provide a system that incorporates some or all of the innovations discussed previously. High Total Dissolved Solids ("TDS") feed water (e.g., seawater or brackish water) is sucked into the primary diaphragm head of a dual-headed diaphragm pump. The primary head of the pump is the larger of the two pump heads. Check valves on the inlet and exit of the pump head force water to be directed in one direction only through the pump head. As feed water discharges through primary pump head **28** (Fig. 1), the feed water enters the feed end of the RO element housing. Water passes longitudinally through the RO element. A portion of the water passes through the membrane producing clean permeate water. The remaining water is higher TDS concentration (relative to the TDS of the feed water) that is retentate discharge from the RO element. The retentate is directed to the second, smaller diaphragm pump head. The ratio of the sizes of the pump heads explicitly defines the recovery of the RO system. With the smaller pump head being, e.g., 70 percent, of the volume of the primary pump head, the recovery of the system is approximately 30 percent. In other words, 30 percent of the feed volume is forced through the membranes of the RO element, thereby producing a permeate volume that is 30 percent of the feed. Various recovery ratios may be used depending upon the configuration of the system, and the fluid being treated. This feature addresses a first benefit of the invention, namely, enhanced recovery.

Incorporating RO elements in the system with a thin feed spacer provide additional capacity to the system. By utilizing the thin spacer, the capacity of an existing RO plant is increased significantly by simply replacing existing technology RO elements with the thin feed spacer elements, and then adding the dual diaphragm pump system to provide the benefits of that system.

Diaphragm pumps produce an inherent pulse to the fluid flow stream. This is by virtue of the reciprocal motion of the pump stroke mechanism. In conventional diaphragm pumps, the stroke of the pump is controlled by an adjustable eccentric mechanism within the gear housing of the pump. This is usually controlled by a control knob or motor drive on the exterior of the pump. The frequency of the pump is controlled by the speed of the drive motor on the pump. Most diaphragm pumps manufactured today can be driven by a variable speed motor. This combination of stroke length and speed control allows variability of all key operational parameters that are important to optimizing the flow characteristics within the RO element. In addition, by monitoring torque on the pump drive motor, the stroke length and frequency are electronically optimized, or tuned, so that the optimal stroke and frequency are established for the RO element size and hydraulic system in question. The optimum conditions are achieved when the torque (or load) on the motor is minimized at the rated flow rate of the membrane element. This feature addresses the benefits from fluid flow pulsing.

Another advantage is realized by connecting the two different sized pump diaphragms together. The feed pressure to the RO element is roughly equal to the retentate (or discharge) pressure from the RO element. Theoretically, flow through the feed spacer in the RO element is zero. Practically, there may be a pressure drop of about ten percent across the element. For purposes of example, assume that there is no pressure drop across the element. This means that the same pressure is applied on the large diaphragm pump head as there is on the small diaphragm pump head. By connecting the two diaphragms with a common shaft, hydraulics in the pump heads set up so that force on the small head opposes, or offsets, the force on the large head. Therefore, the net working force on the pump is equal to the value of the recovery of the RO element. In the example discussed here, the force generated by the small pump head (70 percent) offsets the force on the large head (100 percent) so that the net force required to operate the system is 30 percent. This is defined as pressure recovery. Stated in another fashion, the energy required to operate the RO system is 30 percent of that required to operate a system that is comprised of one diaphragm. Indeed, conventional RO plants use high pressure pumps to

provide the feed pressure for the RO elements, with no attempts to utilize pressure recovery. This feature alone can save 70 percent of the energy required to operate an RO plant.

Thin feed spacers that provide more element surface in the RO element, combined with pressure recovery, can easily produce a 100 percent improvement in kilowatt per gallon of water produced. Pulsing benefits are not impacted by these two features. Pulsing contributes additional benefits that are not degraded by the additional RO surface area or the pressure recovery features.

All five of the benefits discussed above are not necessarily mutually beneficial. For example, the benefits of diffusion may be offset by pulsing.

The system integrates any or all of five features, or combinations thereof, of membrane technology for water treatment. The five features comprise the use of: (1) thin feed spacer spiral wrapped elements; (2) enhanced recovery (ratio of feed to permeate); (3) diffusion effects; (4) fluid pulsing; and (5) pressure recovery. The system offers maximum benefit for reverse osmosis (RO) membranes due to the high working pressures associated with seawater desalination. Those of ordinary skill in the art of membrane technology will recognize that this system also has benefit for fluids other than water, and for membrane technology that includes microfiltration, ultrafiltration, and nanofiltration, in addition to the obvious advantages to RO technology.

The preferred embodiment is illustrated in Fig. 1. As shown therein, pump **20** comprises a diaphragm pump design with two diaphragm heads, primary or feed head **28**, and secondary or retentate head **30**. In an alternate embodiment, the pump can be a plunger type pump, a hydraulic activated diaphragm pump, a solenoid activated pump, or other configuration. One key feature of the preferred pump configuration is that pump **20** imparts a pulsing fluid and pressure wave on the fluid being transferred. Another primary feature of pump **20** is that pump feed diaphragm **72** and retentate diaphragm **70** are connected preferably mechanically by shaft **38,** or

alternatively hydraulically, in order that the fluid pressure acting on retentate head **30** transfers force to feed head **28**. The interconnectivity of feed diaphragm **72** and retentate diaphragm **70** ensures that fluid pressure on the left side of the diaphragm of retentate head **30** partially offsets fluid pressure on the right side of the diaphragm in feed head **28**. This feature provides pressure recovery and significantly reduces the total energy to operate the system versus a system that utilizes feed pressure only.

High TDS feed water (e.g., seawater) enters or is sucked into feed head **28** at feed head inlet port **34.** Lower TDS feed water (i.e., brackish water) or other waters of varying degrees of ion concentration also benefit from this system. Feed head inlet port **34** incorporates a check valve that prevents backflow of water out of feed head **28** during the pressure stroke of pump **20**. Fluid is compressed on the right side of feed diaphragm **72** and is expelled out of feed head discharge port **36**. Feed head discharge port **36** incorporates a check valve to prevent fluid downstream of feed head **28** from returning to feed head **28** during the suction stroke of pump **20**. Fluid discharged from feed head **28** discharge port **36** is transferred to feed inlet port **60** on RO element **22**.

Benefits of thin feed spacer designs in RO elements include more membrane surface per RO element volume, concentration polarization reduction via TDS diffusion effects, and increased surface velocity and shear, all of which contribute to increased RO element throughput and product water quality. Although thin feed spacers are preferable in the system of the present invention, conventional feed spacer elements may also be used. Thin feed spacer elements improve the overall efficiency and throughput of the system because there is more membrane area in the same element size housing.

Permeate, or product water, from RO element **22** is discharged through permeate water port **64**. High TDS retentate water is discharged from RO element **22** via retentate discharge port **62**. Assuming no expansion of RO element **22** and hydraulic lock of the system (no air), the

law of conservation of mass dictates that the volume of water entering RO element **22** inlet port **60** equals the sum of the volume of water discharged at permeate discharge port **64** and retentate discharge port **62.** Recovery in an RO element is defined as the volume of permeate (or product water) discharged from an RO element versus the feed water entering the element. Therefore, the recovery of an RO element is explicitly defined by the ratio of the swept volume of pump **20** feed head **28** versus the volume of retentate head **30**. The difference in volume between the RO element feed volume and the retentate volume is the permeate, or product water, volume.

In order for energy recovery as well as fixed recovery (ratio of permeate to feed) to work, the discharge port retentate head **30** is closed in order for pressure to build up in the system. The ultimate pressure obtained is a function of the osmotic pressure of the feed water in RO element **22**. Closure of the discharge port of retentate pump head **30** is achieved with differential pressure activated (DPA) valve **24**. DPA valve **24** is activated by equal pressures applied across different diameter ports in DPA valve **24.** Pressure is acted on the circular area of the back of piston **50** which is defined by the diameter of DPA valve bore **56.** The force on the back of piston **50** is defined by the pressure multiplied by the area. The force on the front of piston **50** is defined by diameter **54** of inlet port **42.** Since the pressures are unequal (feed and retentate), piston **50** is driven home with greater force on the rear of piston **50** to seal inlet port **42**. Port **42** remains sealed during the compression stroke of pump **20**. On the return stroke of pump **20,** pressure in the system is relieved and there is no net force applied to piston **50** in DPA valve **24** to seal port **42**. On the return stroke of pump **20,** fluid on the left side of diaphragm **70** is driven through port **42** of DPA valve **24** and is expelled out of retentate discharge port **46.** Fluid cannot back flow out of the inlet port of retentate head **30** since RO element **22** is a closed system and check valve **36** in feed head **28** will not allow return of fluid to feed head **28**.

The appropriate fluid pulse amplitude and frequency significantly improves permeate throughput and quality for any given unit area of membrane surface. Due to fluid dynamic considerations, the optimal fluid amplitude and frequency for any given RO element configuration

is unique to that configuration. Amplitude of a diaphragm pump is defined by the stroke length of pump **20**. A shorter stroke produces less amplitude (volume of fluid per stroke). Stroke length (amplitude) is controlled on diaphragm pump **20** by virtue of manual or motor driven eccentric control knob **40**. Likewise, the frequency of the pump stroke is explicitly controlled by the rotational speed of pump motor **26**. By virtue of the appropriate controls, amplitude and frequency can be controlled either manually or electronically. By empirically determining the appropriate amplitude and frequency for a given RO element configuration, the correct amplitude and frequency can be dialed in manually to achieve optimal throughput and permeate quality. Conversely, a feedback control loop can be programmed into a computer to allow the pump to electronically optimize product throughput and quality.

The three key parameters are easily measured. First, energy into the system can be optimized by measuring the amperage load on pump motor **26.** Second, permeate, or product water, quality can be easily measured by optional conductivity meter **74** which measures the TDS in the product water and verifies performance of RO elements. Other types of water quality detectors may additionally be used. The third and final parameter is the permeate flow rate. This is preferably measured by flow transmitter **76**. Alternatively, since the recovery of the system is explicitly defined by the ratio of the swept volumes of feed head **28** versus retentate head **30**, then the permeate flow rate is easily determined by the frequency and amplitude of pump **20**. The frequency may be electronically monitored by the speed of pump motor **26**, and the amplitude may be preferably monitored by the motor position of stroke control knob **40.** Optimization control schemes use hardware and software programmable logic controllers ("PLC"). The system is preferably optimized by using a PLC to monitor the pump motor amplitude and speed, product water quality and flow rate to optimize the efficiency of the system.

Significant features of the system of the present invention are that the two interconnected heads of the pump simultaneously provide: (1) a fixed recovery (ratio of product water to feed water); (2) the two interconnected heads provide energy recovery by transferring force from the

retentate diaphragm to the feed diaphragm; and (3) the pump imparts a pulsing pressure (and fluid) wave on the RO element.

Industrial Applicability:

The dual head pump invention is further illustrated by the following non-limiting example.

Example 1

The present invention was developed under a contract funded the U.S. Department of Defense's Defense Advanced Research Projects Agency ("DARPA") to produce a small portable system that will allow individual soldiers to treat any water anywhere to drinking water quality. The research did not focus on membrane chemistry, but rather construction and hydraulic flow characteristics of spiral-wrapped RO element designs. Concurrent with design of the RO elements, a hand pump device was developed that utilizes various features including a simple differential pressure activated valve to produce pressure recovery in the pump to significantly reduce the applied force required to operate the pump.

Advantages of the invention, as demonstrated by the research, include as follows:

Enhanced Recovery. Recovery is defined as the amount of permeate water (clean product water) divided by the volume of feed water that enters an RO element. Typically, RO elements operating on seawater utilize a recovery of 10 percent or less. Extensive tests were conducted on the membranes to determine the amount of water that can be driven through a membrane and still produce acceptable quality permeate. These studies showed that a 30 percent recovery was feasible using the present invention.

Thin Feed Spacer. The feed spacer in a spiral wrapped RO element was constructed of a plastic web mesh that held the faces of the membranes apart so that feed water could flow longitudinally down the length of the element with minimal pressure loss while allowing the water to cross the membrane. On the opposite side of the membrane leaf was the permeate carrier.

The permeate carrier was a porous but more structurally rigid material that withstood compression from the membrane surface, but allowed the permeate to flow spirally to a central collection tube where the permeate was collected. Current construction techniques limit existing feed spacer thickness to approximately .011 inches thick. Most RO elements utilize feed spacers that are approximately .025 inches thick. Hydraulic calculations indicated that a feed spacer that is .003 inches thick is adequate to allow flow through the element. The primary advantage of a thin feed spacer is that more membrane element material can be wrapped into a smaller diameter RO element housing, thereby significantly increasing the membrane surface in the RO element. More membrane surface equates to more product water throughput.

Diffusion Effect. Concentration polarization is defined as the buildup, or accumulation, of total dissolved solids (TDS) at the surface of the membrane. As water molecules flow through the membrane surface, ions are rejected and are retained on the feed side of the membrane material. This accumulation of ions represents an increase in the TDS at the surface of the membrane, thereby increasing the osmotic pressure required to drive the water molecules through the membrane surface. The negative result is higher operating pressures and lower production. Diffusion effects (tendency of molecules to diffuse uniformly in a solution) were improved with reduced separation between the membrane faces. Coincidentally, diffusion effects were dramatically improved when the separation between the membrane surfaces approached 0.003 inches. Improved diffusion resulted in reduced concentration polarization resulting in higher permeate quality and throughput. Another feature of thin feed spacers that is conducive to lower TDS is the increased fluid shear which is produced with higher fluid velocity that results from equivalent volumes of feed water traversing a thinner feed spacer thickness.

Hydraulic Feed Water Pulsing. Pulsing of the feed stream to an RO element has a beneficial effect for reduction of concentration polarization, and subsequent improvement in product water throughput. Tests conducted verified this effect, and show improvements, in some cases, greater than 100 percent in product water throughput versus steady flow. These same

tests also demonstrated applied pressure reductions of 18 to 19 percent. In other words, in steady flow tests, 800 psi is required to produce acceptable quality permeate. With pulsing, the mean operating pressure that produced the same permeate volume and quantity was 650 psi. Each RO element physical configuration had an optimal frequency and fluid amplitude to achieve maximum performance.

Pressure Recovery via Differential Pressure Activated ("DPA") Valve. During development of the hand held manual RO pump of the invention, a DPA valve was developed that significantly simplified the design of a hand-held RO pump and enabled a pressure recovery feature that significantly reduced the force required to operate the pump. This pump had only three metal parts, namely three stainless steel springs that acted to load check valves in the pump. All other components of the pump were injection molded, thereby producing a simplified RO hand-held pump that is low cost and therefore is disposable.

In-line Pump

Another preferred embodiment of the present invention comprises a two component filtration system comprising a water pump mechanism and a reverse osmosis filter for reducing the level of TDS in the water, preferably resulting in potable water. In the preferred embodiment, the pump mechanism includes a pressure recovery feature that reduces the total force required to overcome osmotic pressure in the reverse osmosis membrane. For reverse osmosis operation, an embodiment of the pumping mechanism includes a mechanism for storing energy on the suction stroke such that the force for operation will be averaged over the suction and pressure stroke, rather than all of the force being applied on the pressure stroke. This mechanism reduces the peak pump force nominally by half when used to reduce TDS in seawater.

In one embodiment, the inventive system is portably configured for ease of carriage in the field. As a non-limiting example, the dimensions of the system, in storage configuration, are preferably approximately 4 inches wide by approximately 4 inches deep by approximately 24

inches in length, and are more preferably approximately 2 inches wide by approximately 2 inches deep by approximately 15 inches in length. The total weight is preferably less than five pounds, and more preferably less than three pounds when dry.

The first major component of this embodiment of the present invention is the pump mechanism. Referring to a preferred embodiment, pictured in Fig. 2, the pump mechanism comprises housing **100**, which is optionally fabricated from any of several materials known by anyone versed in the art of pump and cylinder manufacturing, including but not limited to glass or fiber reinforced injection molded plastic. The cylinder has end cap **102** that is preferably attached to the end of the cylinder by conventional threads or another locking mechanism. One of the major benefits of this design is the in-line configuration of the RO element and the pump piston. This configuration makes the injection molding tooling inexpensive and provides for low cost pump housing parts. This configuration also minimizes post mold fabrication processes. The housing optionally comprises cast or machined aluminum, titanium, steel, or any suitable material that is compatible with high TDS water and high pressure.

The handle end of the pump housing incorporates a check valve **112** on the inlet stream. Inlet check valve **112** comprises ball **116**, spring **118**, and retainer seat **114** inside chamber **120** within housing **100**. Check valve **112** may alternatively comprise poppet, disc, or other sealing mechanisms and springs made of material compatible with the fluid being transferred, for example stainless steel. Spring **118** provides positive sealing of the check valve in any orientation of the pump. Inlet check valve **112** allows fluid to enter pump chamber **126** through intake passage **122** in housing **100** during the suction stroke and prevents water from exiting through the port on the compression stroke. In the preferred embodiment, intake passage **122** is cast into housing **100** during the injection molding process. In alternative embodiments, intake passage **122** is machined in housing **100** or a metal or other appropriate material tube is placed in the mold prior to injection molding. If required, intake passage plug **124** seals any holes or passages required for injection molding or machining but not needed for pump operation. Plug

124 is installed using conventional threads or snap fitting for removable applications and spun or solvent welded for permanent applications. Water entering through inlet check valve **112** of the pump mechanism preferably comprises flexible tube **106** and strainer **104** to filter large particles from the water stream prior to entry into pump chamber **126**. Alternate embodiments eliminate tube clamp **108** and combine tube fitting **110** and retainer seat **114** into a single component.

Traveling in pump housing **100** is piston **128** comprising, for example, injection molded plastic, cast or machined metals, or any combinations thereof, whose materials are compatible with the fluid being pumped. Piston **128** incorporates seals **130** and **132** which isolate pump chamber **126** from retentate chamber **136**. The seals are oriented in the piston ring grooves in such a manner to ensure positive sealing of the different chambers. In an alternative embodiment, the seals comprise piston rings or other sealing technology commonly known by those versed in the art. Piston **128** is moved in and out of pump housing **100** by means of piston shaft **134**. Force on piston shaft **134** is applied by pump jack mechanism described below.

Piston shaft **134** is sealed to cylinder cap **138** by means of shaft seal **140** with sealing means previously discussed. Piston shaft **134** preferably comprises hollow titanium with an injection molded plastic or cellulose core. Alternate embodiments of piston shaft **134** comprise cast or machined, solid, hollow or filled aluminum, steel, stainless steel, or plastic; other suitable material that is compatible with high TDS water and the forces on the shaft; or any combinations thereof. Preferably, cylinder cap **138** and piston shaft **134** allow rapid changes of the recovery ratio (permeate to feed water ratios). This is simply achieved by changing the diameter of piston shaft **134**, which necessitates changing cylinder cap **138** so that the correct bore and seal **140** match the new diameter.

Cylinder cap **138** is attached to housing **100** preferably using conventional threads, or alternatively, other attachment means, and is sealed to retentate chamber **136** by means of end cap seal **144** with sealing means previously discussed. Cylinder cap **138** preferably comprises

injection molded plastic and shaft ware busing **142**, preferably brass. Cylinder cap **138** may alternately comprise cast or machined metal, machined plastic, or any combinations thereof. Other alternate embodiments of cylinder cap **138** eliminate shaft ware bushing **142** and split cylinder cap **138** into two major parts where one part contains the seals and the second part contains the threads. This two-part configuration separates the sealing and threading functions and permits seals to remain stationary while the threads are tightened.

Water is pumped from pump chamber **126** into RO element chamber **184** during the compression stroke. Outlet check valve **172** allows fluid to enter RO element chamber **184** during the compression stroke and prevents water from exiting through the port on the suction stroke. Outlet check valve **172** preferably comprises a rubber umbrella type check valve **174** covering holes **176** in plate **178** integral to housing **100**. In alternate embodiments, plate **178** is a threaded plated screwed into place, a non-threaded plate spun or solvent welded into place, or another assembled mechanism. Other alternate embodiments of check valve **172** comprise ball, poppet, disc, spring, or other sealing mechanisms know by those versed in the art.

RO chamber **184** contains RO element **186**. The annulus between RO element **186** and housing **100** is divided by seal **204** into a feed side, between outlet check valve **172** and seal **204**, and retentate side, other side of seal **204**. The operation of RO element **186** is described in detail below. Briefly, water enters the feed end of RO element **185**, flows longitudinally through element **186**, and emerges either from the other end as retentate or from RO element center tube **188** as permeate. RO element **186** is held laterally in place by spacer **180** with seal **182**, seal **204**, and RO end cap **194.** Spacer **180** and RO end cap **194**, with constraint and pressure provided by end cap **102**, longitudinally hold RO element **186** in place. Seal **192**, between RO element end cap **194** and housing **100**, and seal **196**, between RO element end cap **194** and RO element center tube **188**, prevent water leaking from RO chamber **184** and commingling of retentate and permeate streams. Permeate water exits the invention through flexible tube **202** passing through a hole in end cap **102**. In the preferred embodiment, flexible tube **202** is attached to RO element

center tube **188** by tube fitting **198** and tube clamp **200**. Tube fitting **198** is preferably spun welded inside of RO element center tube **188**. Alternative embodiments for attaching tube fitting **198** to RO element center tube **188** comprise solvent welding, conventional threads, snap or push connection, or other mechanisms known by those versed in the art. Tube fitting **198** may alternately be cast integrally with center tube **188**. Retentate water exits RO chamber **184** through retentate return passage **146** in housing **100** to retentate pump chamber **136**. In the preferred embodiment, retentate return passage **146** is cast into housing **100** during the injection molding process. Retentate return passage **144** may alternately be machined in housing **100** or be a metal or other appropriate material tube placed in the mold prior to injection molding. If necessary, retentate return passage plugs **148, 148A** seal any holes or passages required for injection molding or machining but not needed for pump operation. Plugs **148, 148A** are preferably installed using conventional threads or snap fittings for removable applications, or are spun or solvent welded for permanent applications.

Pressure recovery in the pump occurs as pressure is generated in pump chamber **126**, passes through RO element **186**, and returns through retentate return passage **146** to retentate pump chamber **136**. There is effectively very little flow resistance through RO element **186** from the feed side to the retentate side, and thus very little pressure drop from the feed side to the retentate side. Pressure recovery in the pump occurs because the high retentate pressure in chamber **136** acting on the annular area on the back side of piston **128** (which is the cross section area of piston **128** minus the cross section area of shaft **134**) partially offsets the pressure in pump chamber **126**. The theoretical pressure recovery factor is the ratio of annular area to piston **128** cross section area.

Differential pressure activated (DPA) valve **160** controls the release of the retentate from retentate chamber **136**. The DPA valve comprises poppet **164**, spring **168**, seal **166** and plug **170** inside chamber **162** within housing **100**. DPA valve **160** senses and responds to pressures in pump chamber **126** and retentate chamber **136**. Based on these pressures, poppet **164** is held

(1) in the "closed" position and blocks the discharge line **171** or (2) in the "open" position and exposes discharge line **171**. The termination of discharge line **171** preferably comprises tube fitting **218**, flexible tube **222**, and tube clamp **220**. The preferred location of DPA valve **160** is shown in Fig. 2. In alternate embodiments, DPA valve **160** may alternately be connected in other locations, as long as pump inlet **169** is located between inlet check valve **112** and outlet check valve **172** and retentate inlet **163** is located between the retentate side of RO element **186** and retentate chamber **136**. A more restrictive location of retentate inlet **163** is between the start of retentate return passage **146** and retentate chamber **136**. This more restrictive location allows retentate to be discharged without having the retentate reenter RO chamber **184**.

DPA valve **160** operates as follows. On the compression stroke, pressures in pump chamber **126** and retentate chamber **136** are approximately equal. Pump chamber **126** pressure may be slightly higher than retentate chamber **136** pressure due to pressure losses in RO element **186** or elsewhere in the pump. Poppet **164** is in the "closed" position and blocks discharge line **171** from retentate chamber **136**. Poppet **164** is held firmly in place by applied forces due to the product of the applied pressures and the areas over which they are applied. The design of poppet **164** and chamber **162** are such that poppet **164** area exposed to pump chamber **126** pressure is larger than poppet **164** area exposed to retentate chamber **136** pressure. The differences in exposed poppet **164** areas results in a large force to firmly hold poppet **164** in place during the compression stroke.

On the combined intake/discharge stroke, pressure in pump chamber **126** reduces to zero (gauge pressure) or slightly negative as water is sucked into chamber **126**. Movement of piston **128** during the intake stroke attempts to compress the liquid in retentate chamber **136** resulting in a high retentate chamber **136** pressure. The resulting pressure imbalance between retentate chamber **136** and pump chamber **126** moves poppet **164** to the "open" position and exposes discharge line **171**, allowing retentate chamber **136** liquid to pass through discharge line **171**. Excessive movement of poppet **164** is prevented by plug **170**. At the end of the combined

intake/discharge stroke, flow through discharge line **171** ceases due to lack of fluid, the pressure reduces, and spring **168** pushes poppet **164** into the "closed" position. Poppet **164** and plug **170** preferably comprise injected molded plastic. In the preferred embodiment poppet **164** seats and seals directly against a seat injection molded or machined into housing **100**. Seat end of poppet **164** is optionally covered with rubber or a similar material to assist in seating. Poppet **164** and/or plug **170** may optionally comprise cast or machined metal or machined plastic. In the preferred embodiment, chamber **162** is cast into housing **100** during the injection molding process. In alternate embodiments, chamber **162** is machined into housing **100** or a metal or other appropriate material tube is placed in the mold prior to injection molding.

Pressure relief valve **150** is incorporated into housing **100**. Pressure relief valve **150** preferably comprises ball **154**, spring **156**, and plug **158** inside chamber **152** within housing **100**. Alternative embodiments comprise ball, disc, poppet, spring, or other sealing mechanisms. Pressure relief valve **150** opens and relieves pressure when pressure on ball **154** is sufficient to overcome the force in spring **156** which keeps ball **154** in the closed position. The purpose of pressure relief valve **150** is to limit the pressure in retentate chamber **136** that can be developed by the pump to a safe operating level. The preferred location of pressure relief valve **150** is shown in Fig. 2. In alternate embodiments, pressure relief valve **150** may be located anywhere between outlet check valve **172** and retentate chamber **136**. This span of locations allows pressure relief valve **150** to be effective on both compression stroke and the combined intake/discharge stroke of the pump as desired. In the preferred embodiment, chamber **152** is cast into housing **100** during the injection molding process. In alternate embodiments, chamber **152** is machined in housing **100** or a metal or other appropriate material tube is placed in the mold prior to injection molding.

The second major element of this embodiment of the present invention is a reverse osmosis filter system. Reverse osmosis filters are very efficient filter systems removing very small particles including ions such as sodium and chloride. In order to drive high TDS water

through the RO membrane, the osmotic pressure of the water must be overcome. In the preferred embodiment, this system comprises a conventional spiral wound design RO filter element **186**. In other embodiments, RO filter element **186** comprises ceramic membrane, carbon membrane monotubes, or other RO elements known to those versed in the design of RO elements. High TDS feed water at a pressure exceeding the osmotic pressure flows in to one end of cylindrical filter element **186**. As the water flows longitudinally through the length of filter element **186**, the water runs across the surface of the spiral wrapped membrane to the other end of filter element **186**. As the water flows across the membrane surface, the ions are rejected and water molecules flow through the membrane. As the water flows longitudinally through filter element **186**, the water on the feed side of the membrane surface increases in ion concentration (higher TDS). The higher TDS water coming out of RO element **186** is referred to as retentate. The purified water which has passed through the membrane and into permeate chamber **190** is referred to as permeate.

The recovery ratio of RO element **186** is defined as the ratio of the volume of permeate (finished water) that is expelled to the feed water volume that is generated in one pump stroke in pump chamber **126**. The difference in volume between pump chamber **126** and retentate chamber **136** is uniquely defined by the volume of pump shaft **134**. The recovery ratio of RO filter element **186** is explicitly defined by the square of the ratio of pump shaft **134** diameter to retentate chamber **136** diameter. Further, by the principal of conservation of mass, the feed water volume that enters RO element **186** generated in one pump stroke is the sum of permeate volume expelled plus retentate volume expelled. Thus the permeate volume produced in one stroke of the pump is equivalent to the volume of the portion of pump shaft **134** that is within retentate chamber **136**, or is alternatively determined by the cross-sectional area of pump shaft **134**.

The RO filter assembly as shown in Fig. 2 comprises a separate pressure chamber **184** with seals **192**, **196** and **204** to isolate the inlet feed stream, the retentate rejection stream and

the permeate product stream. The RO filter element **186** can easily be changed by removing end cap **102** and RO end cap **194** and withdrawing RO element **186** from RO chamber **184**. Installation is the reverse procedure. Circular seal **204** on the outside of RO element **186** and inside cylinder housing **100** prevents retentate water from returning to the feed side of the RO filter element.

To achieve mechanical advantage during pumping, commonly known pump jack mechanisms may be employed to force pump shaft **134** in and out of the pump housing **100**. In the preferred embodiment, force on piston shaft **134** is applied by manual force applied to a pump jack mechanism. Optionally, in order to save size or weight, a simple piston may be utilized. Alternatively a piston shaft force generating mechanism comprising a reciprocating motion drive powered by petroleum based fuel drive engines, electric motors, or any other power generating device may be employed. In the preferred embodiment, lever arm **210** length for obtaining the mechanical advantage corresponds to the overall length of pump housing **100**. The end of lever arm **210** is optionally fitted with a large surface area pad **216** to reduce the point source load on the human anatomy. Pad **216** is preferably contoured to be conformal with pump housing **100** to facilitate compact storage. The length of lever arm **210** is optionally removably securable to pump housing **100** or end cap **102** for travel. In the preferred embodiment, housing eccentric **205** is an integral part of housing **100**. In alternate embodiments, housing eccentric **205** comprises a separate part comprising injection molded plastic; cast or machined aluminum, steel, titanium; or other suitable material that is compatible with the pumping forces achieved, attached to housing **100** by conventional threaded fasteners or other means. In the preferred embodiment, lever arm **210** is a one piece injection molded part and is preferably attached to housing eccentric **205** by pin **206** with end clips **208** and to pump shaft **134** by pin **212** with end clips **214**. In alternate embodiments, lever arm **210** comprises one or more pieces of injected molded plastic; cast or machined, solid, hollow, or filled aluminum, steel, or titanium; or other suitable material that is compatible with the pumping forces achieved.

Conventional water filtration using a micron filter typically does not require significant differential pressure to force the water through the filter element. Typical pressures are less than 100 pounds per square inch (psi). However, for reverse osmosis membranes, the pressure to drive the water across the membrane is a function of the TDS in the water. The pressure force required can be significant - several hundred psi. Most hydraulic jack mechanisms have a pressure stroke and a return stroke. The pressure stroke requires force and the return stroke is usually very low force that is associated with friction in the pump device. In the preferred embodiment of the present invention, the pump jack mechanism incorporates an energy storage device to store up energy in the return stroke, as described above. The stored energy is then released on the pressure stroke to ease the force required to implement the pressure stroke. Under ideal conditions at a given TDS level, the stored energy is approximately half of the total force required to drive water through the RO membrane. Likewise, the peak force required of the operator to operate the pump in the power (pressure) stroke is reduced by half.

The preceding examples can be repeated with similar success by substituting the generically or specifically described reactants and/or operating conditions of this invention for those used in the preceding examples.

Although the invention has been described in detail with particular reference to these preferred embodiments, other embodiments can achieve the same results. Variations and modifications of the present invention will be obvious to those skilled in the art and it is intended to cover in the appended claims all such modifications and equivalents. The entire disclosures of all references, applications, patents, and publications cited above are hereby incorporated by reference.